CONTROLLABILITY ASSESSMENT FOR UNINTENDED REACTIONS OF ACTIVE SAFETY SYSTEMS

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ABSTRACT

ISO 26262 requires a controllability assessment for the hazard and risk analysis of automotive E/E systems. Depending on the verifiable controllability, a function may be limited in terms of its intervention options and intensity. For Active Safety Systems this limits their accident-avoidance/-mitigation potential. An analysis of the applicability of ISO 26262 for these systems reveals that it does not address unintended reactions due to incorrect situational analysis of a surrounding perception system, even if the situation for the driver is similar to some of the failure modes. Additionally, the result of the risk assessment depends on the situations chosen. As numerous factors define a driving situation, the possible detailing of these factors is unlimited. Detailing decreases the rate of occurrence of single situations and thereby lowers the required overall safety level. Hence, a method is needed that allows a systematic, verifiable derivation of test situations, including traceability of the detailing. Based on this, for an objective controllability assessment with limited test effort, the minimal sufficient set of relevant scenarios for testing has to be identified.

These scenarios need to have a high probability and impact on controllability. Both factors have to be quantified and evaluated. Based on the analysis of a controllability situation, a strategy is developed to assess the relevance of situations. To quantify the change of uncontrollability in real testing, an objective assessment criterion has to be designed. As a start, the method is applied to emergency braking functions in longitudinal traffic.

The approach begins with the base case and categorizes the factors of a controllability situation. These are weighted with a relevance factor derived from the probability and the controllability. The factor for controllability depends on an assumed or measured increase of uncontrollability caused by the specific situational parameter. By increasing the detailing level, the overall relevance factor for the parameter is derived, to be used on the next less-detailed level.

The assessment criterion for uncontrollability is based on the remaining distance to the point where a crash is unavoidable, the “Point-of-No-Return” (PoNR), and the braking deceleration by the driver. Depending on the driver’s braking force, the PoNR is postponed until the crash will no longer occur. To prove the feasibility of the assessment method, a decelerating leading-vehicle situation is defined. Different deceleration strategies with and without switch-off are used. After initial simulation, the situation is implemented in a real test setup and experiments with naïve drivers are conducted. The results of the objective and subjective evaluation are analyzed and discussed.

The methodology allows the systematic identification of the minimum set of test scenarios for controllability assessment of Active Safety Systems. It quantifies the relevance of influencing factors and in combination with the controllability criterion, can reduce the test effort and increase transferability.

The methodology enhances the controllability assessment according to ISO 26262 [1] to support a systematic choice of controllability test scenarios for Active Safety Systems. A more reliable controllability assessment allows the limits of these systems to be enhanced, increasing the overall traffic safety.

INTRODUCTION

Over the past decade, Advanced Driver Assistance Systems (ADAS) have developed rapidly. Using environment perception systems to assist and support the driver, they are able to avoid a growing proportion of accidents. At the same time, the increasing application of mechatronics-based systems in vehicles means that there is a rapidly growing number of intervention options. The actuators are getting closer to match or even out-perform the capabilities of a human driver. This may lead to the conclusion that traffic safety will soon reach a high level.

To provide safety in public traffic, ADAS depend on information their sensors extract from the surroundings and from the driving situation. Based on this information, they need to predict the situation in the near future and find a suitable and safe counteraction. In most cases, such counteraction is dependent on the present status of the driver. For example, if the driver is distracted, an early warning might be suitable. If the driver is aware of the situation this warning will possibly be too early, a phenomenon often referred to as the "warning dilemma" [2].

To provide reliability, the system needs to be at least as good as the driver in its cognition and perception of the specific situation. Even then, the decision of the driver and the decision of the system may diverge, leading to a reaction which is unintended by the driver.

For public traffic it is necessary to prove that hazards due to failures or unintended reactions are reasonably low. Requirements for the risk assessment of safety-critical electric and electronic systems in case of failures are provided in ISO 26262 [1].

For present-day ADAS, the limiting factor is assumed to be a lack of information or lacking information reliability especially in complex situations. Hence, unintended reactions that may cause potentially critical situations cannot be ruled out completely. To overcome this and still provide safety, a common approach is to limit the operational range of a function. Examples are the limitation to a speed-range or the reduction of the duration and/or the intensity of the intervention [3]. In doing this, the safety performance may be limited as well.

By improving the risk assessment in case of failures or unintended reaction, it is expected that the safety performance can be increased.

REQUIREMENTS OF ISO 26262 AND EXISTING TEST METHODS

ISO 26262 [1] established in 2011 provides requirements for safety processes for electric and electronic systems in the automotive industry. Within the "Hazard and Risk Assessment", potential failures, the resulting hazards and their causes, have to be identified. To assess the risk, the exposure (E), the controllability (C) and the severity (S) of a hazard have to be estimated and classified in stages (for example C1 – Simply controllable to C4 – Difficult to control or uncontrollable) [1]. Based on these classes, the Automotive Safety Integrity Level (ASIL) is derived according to Table 1.

Table 1.
ASIL Determination Matrix [1]

		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

The ASIL defines the safety requirements of the soft- and hardware components of the function. For example ASIL B requires a maximum allowable random hardware failure of less < 10^{-7} per operating hour [1].

The applicability of ISO 26262 to the case of unintended reactions can be questioned, as it is intended to apply to the functional safety of electric and electronic systems for vehicles up to 3.5 t. Strictly speaking, the approach described there is not necessarily feasible for unintended reactions of ADAS. In these cases, the system works within its specification and a "failure" results from differences between the situation assessment of the driver and of the system. Therefore, unintended reactions are difficult to detect. In contrast to random hardware failures, the expectable rates of misdetection and misinterpretation of a system can be closely connected to the situation and to the utilization profile. As the resulting situation for the driver or other involved persons are considered to be equal, the methodology and testing approach is assumed to be transferable to unintended reactions. However, it is questionable whether the absolute failure rates used for ASIL determination are allowed to be transferred to this problem [3].

According to the processes of ISO 26262, the exposure of the system to a specific situation and the controllability of the incident resulting from the unintended reaction are the two factors that could be influenced in the development of systems. They determine the relevance of potential hazardous situations and thereby allow the identification of the most critical elements for the approval of systems.

Applicable state-of-the-art methods for the assessment of controllability according to ISO 26262 are summarized in the "Code of Practice" [4]. In there, studies with naïve drivers are recommended as they have high validity. However this method is considered to be very time consuming. To achieve an assessment on level C2, at least 20 valid trials are required, without one single uncontrollable event. A detailed statistical analysis shows that the chances of success for this approach are considerably low at 20 trials [5].

Fach [6] describes a controllability study in a dynamic driving simulator, using the crash/no-crash criterion as suggested in the Code of Practice. Neukum [7] uses trials in public traffic to research the controllability of an Adaptive-Cruise-Control function using subjective and objective values for assessment. A combination of a driver model with measurement data of endurance runs is described by Ebel [3]. Again the crash/no-crash criterion is used.

To supplement these techniques and enhance the transferability of results, an additional method for identification of the minimum set of test scenarios and an adjacent assessment method for controllability is developed.

SITUATIONAL DETAILING AND RELEVANCE

For the assessment of controllability, it is necessary to identify situations suitable to reveal the controllability of an unintended system reaction or a system failure. To limit the amount of testing required for the approval, the situations used for testing should be of high relevance for the real use of the vehicle. As a driving situation could be composed of a nearly infinite number of parameters, a methodology for the systematic identification of the minimum set of necessary test cases has to be defined.

Selection of Test Situations

Different approaches for the choice of test situations are used. A common method is the worst case selection, where all relevant parameters are set to the condition where they are assumed to influence the situation in the most negative way. The intention is that the result of this measurement is the worst possible in all situations. If, for example, a controllability approval could be reached in worst case conditions, all other possible situations will have a higher controllability and be less critical. At the same time, the probability of a combination of all situational parameters in the most negative way is assumed to be very low. This approach thereby overestimates the risk in real traffic and may lead to unnecessary limitations of the functionality of a safety system.

Another approach used in validation is to define specific test cases based on the requirements for the function and/or for the adjacent use-cases. In the case of unintended reactions of the function, the exact opposite is needed. Theoretically, these are all possible situations minus the use-cases defining the requirements [8]. In theory a “brute force approach” could also be applied. In this approach all possible situations are identified by combining as many situational factors as possible. The effort for the brute force approach is very high. In addition it is not assumed to be successful in many cases, as it faces two challenges. First, the set of parameters is only theoretically finite, but in practice too high, so there is always a possibility that one parameter has been left out. Second, calculating the probability of the testing situation, by multiplying the probabilities of every situational parameter will result in a situation with very low probability. In line with the methodology of ISO 26262, the exposure factor of all situations could then be so low, that even with a controllability of C3 every function does not need an ASIL of higher than “A” (see Table 1). The more situational parameters used, the more the exposure and thereby the relevance of the single testing situations decreases.

To cope with these challenges a supplementary methodology for the identification of the necessary set of test cases needs to allow the detailing of situational factors on different levels and must take into account the relevance of situational parameters in terms of probability and controllability variation. Additionally it should allow for being based on an “incomplete” set of situations and give assistance in choosing where further detailing may be useful.

To achieve this, the driving situation is analyzed to identify influencing parameters in terms of controllability. These parameters are then classified and detailed within their classes. Based on this, an assessment method is described that considers the change of controllability caused by these parameters and their relevance regarding the use profile.

Parameter of Controllability Situations

The driving situation is composed of many parameters. A common approach is to cluster these in three categories [9]:

- Environment: e.g. weather, lighting, friction coefficient, road, other traffic participants…
- Driver: e.g. driving education, attention, driving capabilities, internal model, fatigue…
- Vehicle: e.g. technical condition, speed, acceleration…

In a generic approach, starting with these three categories, variation factors are identified. Following the approach of ISO 26262 some can be ruled out. For example the technical condition of the vehicle is defined there as "good". Similarly, considering driver behavior, only short term factors have to be taken into account [5]. To avoid interdependencies, the parameters chosen for the situation definition should be as independent of each other as possible.

The influences of these parameters on the controllability of an unintended reaction are then divided in three elements: causes, hazards, and reaction-limiting factors. Based on this, a set of parameter classes has been identified. Table 2 shows the set of parameters used in this paper and examples of their influences on the controllability situation. The parameter *K* represents the index for this class for detailing.

Table 2.
Situational Parameters

Class	Parameter	*K*	Examples of Influences
Environment	Illumination	1	Driver Perception Time
	Precipitation	2	Driver Perception Time, Friction Coefficient
	Traffic Density	3	Hazards, Complexity of traffic situation
	Road Category	4	Lateral Space, Range of Sight
Driver	Visual Distraction	5	Driver Reaction Delay
Vehicle	Lateral/ Longitudinal Acceleration	6	Available Lateral/Longitudinal Force for Avoidance

This set is not necessarily complete and can be discussed, but nevertheless it is considered to be appropriate as a starting point to investigate the feasibility of the controllability assessment method outlined in this paper.

Relevance Weighting on Detailing Levels

As the controllability proportion (p_C) of a function is assumed to be a high proportion (for example C2 ≥ 90 %) of the overall driver collective, for testing it is more feasible to measure its counterpart, the uncontrollability proportion (p_u) according to Equation 1.

$$p_u = 1 - p_C \qquad (1).$$

The reference for the calculation is the controllability level which needed to be approved (for example C2 representing p_{C2} = 90 % and p_u = 10 %).

A situation identification is made for every parameter class in isolation and starts with the identification of the "base case". The base case is a situation which has a high probability, and a high level of controllability. Most changes to situational parameters will thereby lead to a decrease of controllability. Preferably, the base case is simple to reproduce in a testing environment and has an unambiguous impression on the driver.

The detailed parameters have to exclude each other. Every class is split up in more detailed "categories". As the classes are independent of each other, the sum of all probabilities in the categories (on the higher detailing level) adds to hundred percent. In addition and in order to model uncertainties, a "residue" proportion can be added if, for example, no data is available.

The exposure probability of a parameter value ρ and the weighting factor g are characterized by their indices. The first index (K) represents the class according to Table 2 with values from 1 to 6. The category index on the first detailing level is q. For each more detailed "sub-category" another index (r,s,t…) has to be added, ranging from 1 to the number of detailing subcategories. The dimensions of detailing (sub-)categories could vary.

For every parameter category value q, its exposure probability ($\rho_{K,q}$) is weighted with the weighting factor ($g_{K,q}$) defined as the uncontrollability level (Equation 1) for this specific parameter according to Equation 2.

$$g_{K,q} = p_{u,K,q} \qquad (2).$$

The overall probability vector ($\overrightarrow{W_{K,q}}$) in the respective category q is composed of the probabilities on the next more detailed subcategory (in this example with index $r = 1,2,3,\ldots,n$) according to Equation 3.

$$\overrightarrow{W_{K,q}} = \begin{pmatrix} \rho_{K,q,1} \\ \rho_{K,q,2} \\ \rho_{K,q,3} \\ \cdot \\ \cdot \\ \cdot \\ \rho_{K,q,n} \end{pmatrix} \qquad (3).$$

The overall probability vector is allocated to the weighting vector $\overrightarrow{G_{K,q}}$ composed similarly according to Equation 4.

$$\overrightarrow{G_{K,q}} = \begin{pmatrix} g_{K,q,1} \\ g_{K,q,2} \\ g_{K,q,3} \\ \cdot \\ \cdot \\ \cdot \\ g_{K,q,n} \end{pmatrix} \qquad (4).$$

The scalar product of these two vectors is the weighting factor on the next lower detailing level ($g_{K,q}$) (see Equation 5).

$$g_{K,q} = \overrightarrow{W_{K,q}} \cdot \overrightarrow{G_{K,q}} \qquad (5).$$

To fulfill the condition that parameter values on same detailing level are excluding each other, Equation 6 must be valid.

$$\sum_{r=1}^{n} \rho_{K,q,r} = 1 \qquad (6).$$

Quantification of the Required Detailing Level

The detailing of each situational factor causes effort and requires the collection of additional data. To limit the necessary detailing, a stop criterion is defined. Following the ASIL determination method (see Table 1), the overall controllability for a higher detailing level is only significant if the weighting factor of a parameter in relation to the others on the same detailing level is higher than 10 %. This leads to the stop criteria for further detailing of parameter values according to Equation 7.

$$\rho_{K,q,r}\ g_{K,q,r} \cdot 10 < \max\left(\overrightarrow{W_{K,q}} \cdot \overrightarrow{G_{K,q}}\right) \qquad (7).$$

Exemplary Application on Situational Parameters

An environmental factor influencing the driving situation is precipitation. Different forms of precipitation have to be expected in common driving situations. Accordingly, the class "Precipitation" is divided into categories of values excluding each other. These categories are then detailed into subcategories by the strength of precipitation. Table 3 shows the categories, meaning the first detailing level, with exemplary subcategories (second detailing level) and their definitions according to [10].

Table 3.
Example for Categories of Precipitation

Parameter Class	Categories (1st Detailing Level)	Exemplary Subcategories (2nd Detailing Level)	Definition
Precipitation	Without (Base Case)	-	-
	Rain	Violent	> 50 mm/h
		Heavy	10 – 50 mm/h
		Moderate	2 – 10 mm/h
		Slight	< 2 mm/h
	Snow/Ice	Hail	Snow/Ice, Pellets, Hailstones
		Heavy Snow	> 4 cm/h
		Moderate Snow	0.5 – 4 cm/h
		Slight Snow	> 0.5 cm/h
	Fog	Aviation Fog	200 – 1000 m
		Thick Fog	50 – 200 m
		Dense Fog	< 50 m

For clarity reasons, hybrid types such as sleet or freezing rain are not included. If considered to be of relevance, they have to be given their own subcategory. The analysis of similarities concerning the resulting effects on the driving situation may then allow a similar controllability value to be allocated, for example as the value used for light snow.

Following the division to classes and categories, the probability of the factors is needed. If no data is available, the factor has to be included in the "residue". Consequently, availability of data is crucial for the evaluation process. If the data is not available or not considered valid, for a conservative and safe approach the lowest controllability value must be assigned. This concludes that even a small residue causes a low overall controllability.

The data for the probability of parameters used in this example is based on literature [11, 12]. The example includes the first detailing level only, as no reliable statistical data is available for a more detailed analysis. The controllability values and the proportion of the residue are estimated. As no data is available for the base-case it is derived using Equation 8.

$$\rho_{2,1} = 1 - \sum_{q=2}^{5} \rho_{2,q} \qquad (8).$$

The result of the relevance weighting according to the described method is shown in Table 4.

Table 4.
Relevance Weighting for the Class Precipitation

g_1	Categories	q	$\rho_{2,q}$	$g_{2,q}$ (estimated)	Product $\rho_{2,q}\, g_{2,q}$
0.070	Base Case	1	0.83	0.05	0.042
	Rain	2	0.09	0.1	0.009
	Snow/Ice	3	0.03	0.5	0.015
	Fog	4	0.04	0.1	0.004
	Residue	5	0.01	1	0.010

The example shows that even this very small residue has a big influence on overall controllability. However, an approval on level C2 ($p_u = 10$ %) is possible in this configuration, if the estimated controllability proportions can be proven for the specific cases.

In summary, the methodology is very dependent on the availability of consistent valid data of occurrence rates for situational parameter and a valid controllability assessment. In addition the methodology is dependent on a good initial controllability estimation to identify the most relevant cases which are worth a detailed analysis or even testing with naïve drivers. In the present paper a simulation model is used for this preliminary estimation.

ASSESSMENT OF CONTROLLABILITY

For the assessment of the situational relevance a controllability criterion is needed. The "Code of Practice" [4] defines the criterion for controllability on a nominal scale. It differs depending on whether or not the reactions of the involved persons are able to avoid the crash. For controllability testing with naïve drivers a more detailed criterion is needed which enables statistical analysis by calculating mean values and variance in the collectives. Therefore, a scaled value with an absolute reference has been developed.

Every driving situation starts on a latent danger level, and the occurrence of an incident leads to an ascent of the actual danger level. Without a counteraction the danger increases until it reaches the level where a crash occurs. A possible counteraction can be carried out by the driver to avoid the crash.

To assess the controllability of a situation at least two requirements must be met. First, the situation must be critical and threatening for the driver to trigger an urgency or emergency reaction [13]. Second, there must be enough reaction time left for the driver to perceive the situation and perform an intervention maneuver, otherwise the controllability will be zero in any case.

From this last requirement it is concluded that there is a limit where the driver needs to start the intervention maneuver to be able to avoid the crash. To describe this limit a distance-based approach is used. In the following this minimum reaction distance is called the Point-of-No-Return. If the driver reacts before reaching the Point-of-No-Return, the next question is whether the reaction was appropriate and intense enough to avoid the collision. Defining the Point-of-No-Return as the last possible distance for starting a lateral or longitudinal intervention means that the intensity of the counteraction needed for intervention increases from the start of the situation to that point where it reaches its maximum and is limited by the maximum longitudinal or lateral force available. This criterion is similar to the Time-to-React (t_{tr}) criterion in a time-based approach. A criterion for controllability situations in longitudinal traffic based on the Point-of-No-Return criterion is described below.

Controllability Criterion

The basic situation is assumed to be a decelerating leading vehicle. In most cases, the driver reacts to that potentially critical situation by braking [14]. The interface for deceleration of the vehicle is the braking pedal and the force the driver applies to it, resulting in a specific travel of the pedal. The brake pressure leads to a deceleration and thereby to a change in the relative accelerations between the two vehicles. The absolute deceleration is mainly limited by the friction coefficient. This limitation leads to a last point where a collision can still be avoided by the driver, the "Point-of-No-Return". Neglecting differences in the brake dwell time (τ_B) between vehicles, the Point-of-No-Return is only dependent on the situational parameters relative velocity (v_{rel}), relative deceleration between the vehicles (D_{rel}) and maximum relative deceleration ($D_{max,\, rel}$). It is determined by the maximum longitudinal deceleration (D_{max}) and the deceleration of the leading vehicle (D_{target}) (see Equation 9)

$$D_{max,rel} = D_{max} - D_{target} \qquad (9).$$

For a constantly decelerating leading vehicle and, for simplification, neglecting the dwell time (τ_B), the Point-of-No-Return can be calculated by Equation 10 [15].

$$d_B(v_{rel}, D_{max,rel}) = \frac{v_{rel}^2}{2\, D_{max,rel}} \qquad (10).$$

Plotting the actual distance between the two vehicles over the squared relative velocity leads to linear relations for a constantly accelerated situation. The resulting graph is not linked with the time but rather directly referenced to the physical contact between the vehicles (d = 0). Thereby, reactions of the driver or a safety system can be depicted and compared to the original situation (without reactions of driver/system) in the same diagram. Figure 1 shows an example for a situation of a constantly decelerating leading vehicle with and without driver reaction.

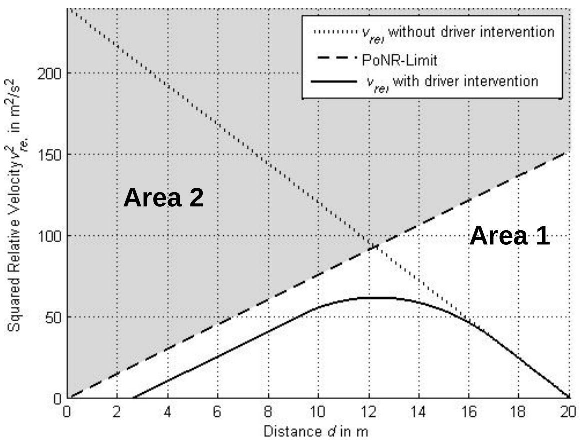

Fig. 1: Controllability graph for D_{target} = 6 m/s² with and without driver intervention

The plot enables an easy identification of the controllability. As long as the relative velocity plot is completely located within area 1, the whole situation is controllable. The closer it gets to the Point-of-No-Return-Limit, the more critical the situation would be. Crossing the limit into area 2 the situation will become uncontrollable. Therefore, in addition to the binary crash/no-crash criterion, the plot provides the option of identifying the minimum distance to the Point-of-No-Return within the whole situation ($d_{min,\ PoNR}$).

Assuming the driver does not decrease brake force as long as the situation is critical, it also enables prediction based on the pending decelerations. In Fig. 1 for example, in the event of driver intervention the deceleration reaches a steady state at a distance of 9 m and can be extrapolated.

For each situation it has to be taken into account whether the target comes to a full stop. In this case D_{target} will be zero and the Point-of-No-Return-Limit is defined by D_{max} only. This is also the case for a switch off of the deceleration of the leading vehicle after a defined period. So the results of such a limitation can be analyzed in aftermath. Figure 2 shows the effect of a switch off or stopping target on the Point-of-No-Return.

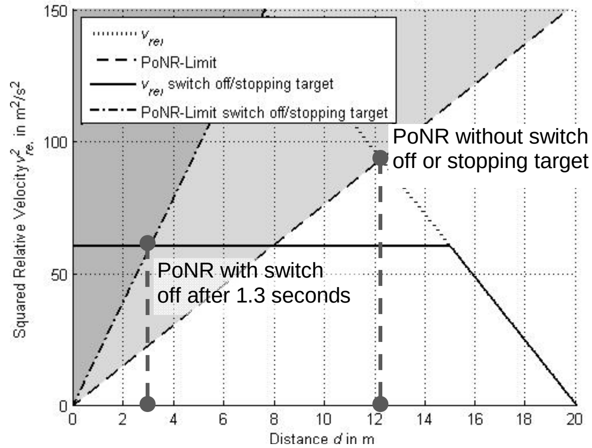

Fig. 2: Controllability graph with D_{target} = 6 m/s² without driver intervention

For the analysis and modeling of driver reactions, a time based view is needed in addition. Human processing and action parameters are often measured on a time base. Examples are the overall reaction time, mental processing time or foot movement time [16]. The reaction time limits including the dwell time, can be calculated backwards from the Point-of-No-Return as a function of the relative velocity (v_{rel}) and the distance (d) and included in the controllability graph.

To be able to react in an appropriate way, the driver must perceive and anticipate the situation. To quantify at which point this is possible, the approach relying on the change of the picture size is used. According to [19] the distance at which the likelihood that the driver is able to estimate the criticality of a situation is higher than 50 % ($d_{limit\ 50\ \%}$) is derived based on the width of the target (B_{target}) and the relative velocity according to Equation 11.

$$d_{limit\ 50\ \%} = \left(\frac{B_{target}\ v_{rel}}{0.003\ s^{-1}}\right)^{\frac{1}{2}} \qquad (11).$$

Based on this criterion the, time between the beginning of the situation and $d_{limit\ 50\ \%}$ is derived ($t_{est\ 50\ \%}$).

Choice of Controllability Situations

For identifying situations which are suitable and relevant for controllability testing, in the first step potential hazards are analyzed. For the described scenario, a hazard results from a decelerating leading vehicle in combination with a limited time gap (τ), thereby limiting the reaction time for the driver of the following vehicle. According to the situational parameter classification in Table 2, distances are a characteristic parameter for traffic density (K = 3) in longitudinal traffic.

The deceleration of the target vehicle depends on the braking strategy implemented. It determines the development of the situation and the perceivability by the driver. For the present study, braking strategies covering different collision-avoidance variants used on the market are implemented. In addition to constant, full and partial deceleration, a staged strategy is used, as the anticipation for the driver is expected to be more difficult in this case.

In the event of an unintended reaction of the system, it is possible, that the driver of the leading vehicle overrides the braking and thereby switches it off after a specific time period. Additionally it may be an option to switch off the intervention of the collision avoidance or mitigation system after a specific time period, if no driver reaction is detected. This limitation enables to keep the controllability at a high level, if unintended reactions are unavoidable [3]. In [15] a minimum time span of 1.3 seconds is used wherein all drivers are expected to have reacted in case of emergency braking. Based on this, for every strategy a switch off after 1.5 seconds is additionally taken into account. Table 5 sums up the braking strategies used.

Table 5.
Deceleration Strategies of Target Vehicle

Name	Deceleration D_{target}	Duration
Partial with Switch Off (SO)	6.5 m/s^2	1.5 s
Partial		To Full Stop
Full with Switch Off (SO)	9 m/s^2	1.5 s
Full		To Full Stop
Staged with Switch Off (SO)	Stage 1: 3 m/s^2	0.75 s
	Stage 2: 9 m/s^2	0.75 s
Staged	Stage 1: 3 m/s^2	0.75 s
	Stage 2: 9 m/s^2	To Full Stop

The strategies are combined with suitable time gaps (τ) to compose a driving situation with potentially critical controllability. Following the detailing approach, the classification of time gaps and their probability is based on statistical data of driver behavior according to [20] and [18] and clustered in parameter categories in Table 6.

Table 6.
Classification of Time Gaps

	Parameter Class: Time Gap (K = 3)		
	Categories: 1st Detailing Level		
τ	0.7 – 1.0 s	1 – 1.8 s	≥ 1.8 s
q	1	2	3
$\rho_{3,q}$	0.25	0.5	0.25
Comment		Base Case	

Longer time gaps increase the available reaction time for the driver. Thereby, test results of the base case ($q = 2$) can be used for a controllability estimation in category $q = 3$. It can be questioned whether category $q = 1$ has to be considered for controllability assessment, as time gaps below 0.9 seconds are less than half the legal distance and result in a fine, but some drivers do follow at these time gaps [20]. Even though the ISO requires the assessment to cover foreseeable misuse, how to handle cases where the driver intentionally takes a higher risk is an issue that has to be discussed.

Simulation for Initial Controllability Estimation

To obtain the preliminary controllability estimation, a simulation model is used. It represents a decelerating-leading-vehicle-scenario and is capable of simulating the coefficient of friction, speed and deceleration strategy of the leading vehicle. In the past, many studies have gathered data of different elements of the driver reaction in emergency braking with varying situational parameters (see [16], [17] and [18]). These studies provide likelihoods of reaction times, enabling calculation that a driver will react within a specific time (see Table 7).

Table 7.
Reaction Times [17]

	Basic Reaction Time	Foot Movement Time (Emergency Braking)	Transient Brake Time
5 % Limit	0.13 s	0.13 s	0.1 s
Median (t_{react})	0.40 s	0.18 s	
95 % Limit	0.73 s	0.25 s	

The limits of reaction times according to Table 7 lead to fixed time intervals calculated backwards from $t_{tr} = 0$ (equivalent to the Point-of-No-Return distance-wise). The resulting time intervals ($t_{99\,\%}$, $t_{90\,\%}$ and $t_{50\,\%}$) assuming a combination of the distributions of each reaction time element are shown in Fig. 3.

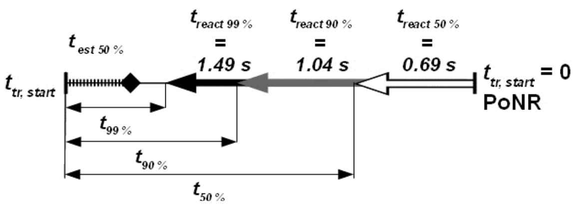

Fig. 3: Time intervals approaching the Point-of-No-Return

The time interval required to obtain a 50 % chance of a correctly estimating the remaining time to collision ($t_{est\ 50\ \%}$) depends on the situation parameters.

The simulation is used to identify the time from the beginning of the situation to the 99 %- ($t_{react\ 99\ \%}$), the 95 %- ($t_{react\ 95\ \%}$) and the 50 %-Limit ($t_{react\ 50\ \%}$) of reaction time and the corresponding controllability levels.

The time gaps chosen for the simulation represent the category ranges according to Table 6. Assuming that uncontrollability increases with decreasing time gap, a value in the lower half of the range τ_{start} = 1.2 seconds is chosen for category q = 2. The simulations are carried out for an initial speed of both vehicles (v_{start}) of 60 km/h. Results are shown in Table 8. Low values for $t_{99\ \%}$, $t_{95\ \%}$ and $t_{50\ \%}$ indicate possibly critical controllability situations.

Table 8.
Simulation Results for τ_{start} = 1.2 s

	$t_{est\ 50\ \%}$ in s	Reaction Time in s (according to Fig. 3)			$t_{tr,start}$	Target Stops
		$t_{99\ \%}$	$t_{90\ \%}$	$t_{50\ \%}$		
Partial SO	0.11	1.03	1.48	1.83	2.52	No
Partial		0.11	0.56	0.91	1.60	
Full SO	0.07	0.05	0.50	0.85	1.54	No
Full		1.19	1.64	0.83	1.52	Yes
Staged SO	0.22	0.50	0.95	1.99	2.68	No
Staged		1.03	1.48	1.30	1.99	Yes

On the basis of the simulation, the conclusion for real testing is that every situation is expected to be controllable for all drivers. To verify these simulation findings, real tests are carried out with naïve drivers.

To estimate the controllability for lower time gaps, the time gap of τ_{start} = 0.9 (q = 1) seconds is simulated too (Table 9). Potentially critical controllability situations are highlighted in grey.

Table 9.
Simulation Results for τ_{start} = 0.9 s

	$t_{est\ 50\ \%}$ in s	Reaction Time in s (according to Fig. 3)			$t_{tr\ start}$	Target Stops
		$t_{99\ \%}$	$t_{90\ \%}$	$t_{50\ \%}$		
Partial SO	0.06	0.30	0.75	1.10	1.79	No
Partial		-0.24	0.21	0.56	1.25	
Full SO	0.04	-0.97	-0.52	-0.17	0.52	No
Full		-0.97	-0.52	-0.17	0.52	No
Staged SO	0.12	0.66	1.11	1.46	2.15	No
Staged		-0.47	-0.02	0.33	1.02	No

As expected, the available reaction times are reduced. For full braking, following the combined distribution, controllability is expected to be approximately 30 %; a switch off does not change the situation anymore. For staged braking without switch off, controllability is expected to be above 90 %. For partial braking without switch off, controllability is expected to be above 95 %. The other reaction times decrease but the reduction in the time gap does not bring about any considerable change in terms of assumable controllability.

While it would be helpful to validate these assumptions by real testing, preceding studies have shown that it is rarely possible to motivate naïve drivers to follow a leading vehicle so closely within the described test setup.

Test Procedure and Layout

For testing with naïve persons a real accident is not possible. However, different techniques can simulate appropriate situations. For example [6] uses a dynamic driving simulator for controllability studies. The validity of simulator findings can be questioned if a critical situation is perceived as threatening due to its virtual impression and in some studies different reaction times have resulted [16]. To overcome this with tests in reality, deformable targets are available. While they provide the option of real contact, they have trade-offs in real appearance.

For the described controllability criterion, it is sufficient to measure the reaction to the point where no Time-to-React is left or a steady state of deceleration is reached. Subsequent reactions can reduce the severity of the crash if the maximum braking force is not reached at the end of the measurements.

A suitable tool providing a highly realistic situation for the following driver is the Experimental

Vehicle for Unexpected Target Approach EVITA [21] (see Figure 4).

Fig. 4: EVITA Tool

The trailer with the real rear-end of a passenger vehicle, called “dummy target”, is connected to the towing car by a cable and a cable winch. By opening the brake on the winch and braking the dummy target, a relative velocity to the following vehicle is built up. If a critical relative velocity and distance is met, the winch brake is closed, reaccelerating the dummy target to the speed of the towing car.

It is able to simulate a critical situation in longitudinal traffic with predefined target decelerations without endangering the test persons. It autonomously avoids the accident by applying an acceleration of 2 g to the target to reduce the relative velocity to zero. It has been proven in preceding studies that the test procedure leads to driver reactions similar to real emergency braking situations [20]. The target vehicle of EVITA is used to simulate an unintended deceleration of the leading vehicle due to a false activation. The initial conditions for testing are similar to the simulation conditions. As the drivers are in charge of keeping a constant distance, the time gap at the beginning of the situation varies within 1.2 and 1.5 s.

The following test vehicle, named ego vehicle, is equipped with a radar sensor that measures the relative velocity and the relative distance between the two vehicles. As a reference, the absolute speed of the ego vehicle is measured. The ego vehicle is equipped with a mechanical brake assistant that supports the driver in an emergency stop. In addition the driver´s behavior and foot movement are recorded by high speed cameras showing the driver´s face, the pedals and the headway.

The tests are carried out on a closed test track with test persons who are not informed about the intentions of the testing. In addition to the objective values of controllability, every test person has to answer a questionnaire evaluating the subjective controllability.

The EVITA Tool is capable of simulating a minimal Time-to-Collision of approximately 0.9 s, before it is accelerated. Depending on the scenario and the driver reaction, the Point-of-No-Return cannot be reached in every case. In the event of early and intense driver reaction, this is in fact very likely. To identify $d_{min,PoNR}$ in these cases, the deceleration of the ego vehicle at the end of the test, marked by the acceleration of the EVITA target vehicle, is extrapolated at a constant level. This approach is considered to be conservative, as it refuses the option of the driver to increase the brake pressure later in the situation. In case the driver reacts early, this method may lead to situations where the collision cannot be avoided by the deceleration of the ego vehicle at the end of the test even though there is enough time left to intensify the brake pressure and avoid the collision. To determine this in case of uncontrollable trials, the time to apply full deceleration is calculated additionally.

Test Results

The measured data are analyzed to identify the driver reaction times, defined as the time to contact the brake pedal, the minimum distance to the Point-of-No-Return in testing ($d_{PoNR, test}$) and the extrapolated end distance ($d_{min, end}$) assuming constant accelerations. Figure 5 shows an example of testing data with extrapolation.

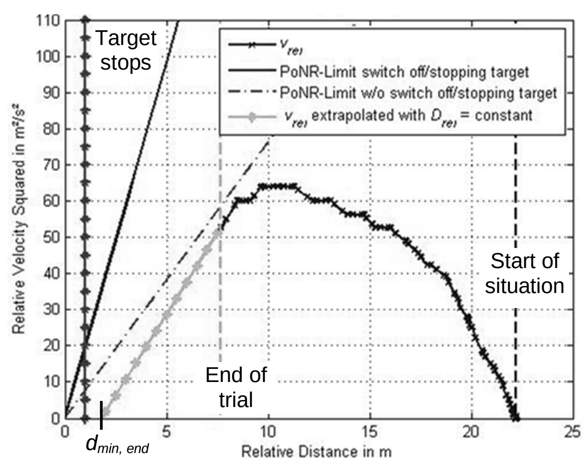

Fig. 5: Example measurement data with extrapolation

Driver reaction times are measured from the beginning of the situation to the contact with the brake pedal, including the mental processing time and the movement time. Figure 6 shows the results of the reaction time in a cumulative distribution function, including the $t_{est\ 50\ \%}$ values based on the simulation, which are illustrated as vertical lines in corresponding colors.

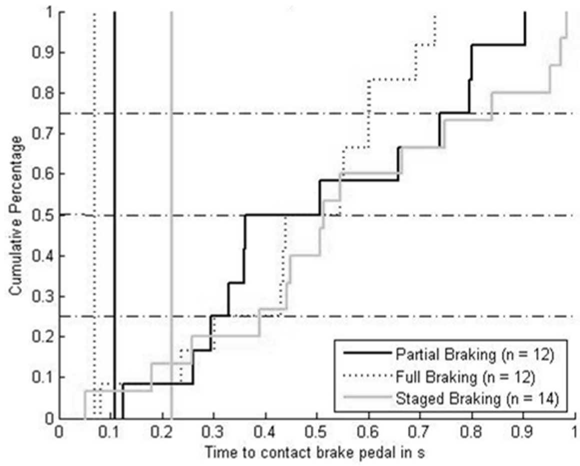

Fig. 6: Reaction Times depending on braking strategy

These results mainly match the preceding assumptions about the reaction times according to [18], but lack the proportion of reaction times above one second.

The cumulative distribution of the maximum deceleration reached at the end of the test is shown in Figure 7.

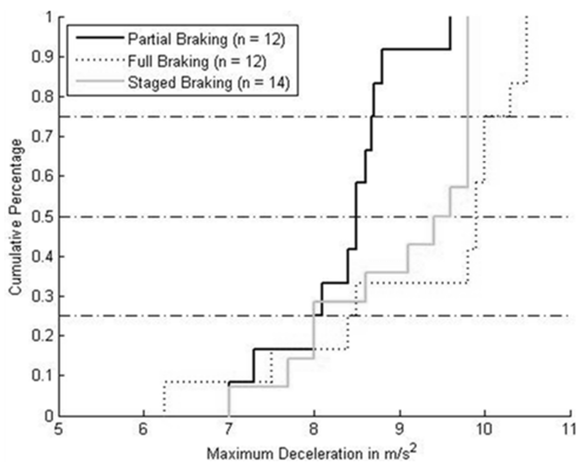

Fig. 7: Maximum decelerations depending on braking strategy

The distribution shows that the intensity of braking depends on the deceleration of the target. For full braking, the distribution can be falsified to follow a normal distribution. For partial and staged braking no statement can be derived. Partial braking and full braking can be proven to be significantly different. This indicates that the driver's reaction depends on the evolvement of the situation.

In the next step, the controllability proportion is analyzed based on the extrapolation with constant acceleration with and without switch off of the braking. Figure 8 shows the minimum distances to the target at $v_{rel} = 0$ ($d_{min,end}$) with switch off.

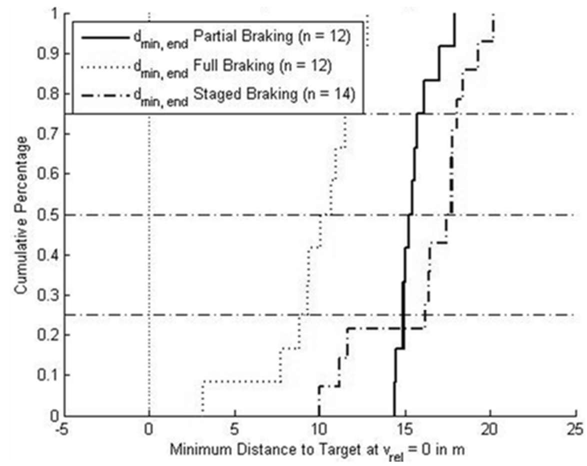

Fig. 8: Minimum distance to target extrapolated for braking strategies with switch off

The differences between partial and staged show nearly significant differences (α = 5.38 %) the others are significant different to each other. However all tests are controllable if the braking of the target is switched off after 1.5 s.

In comparison, Figure 9 shows the results without switch off.

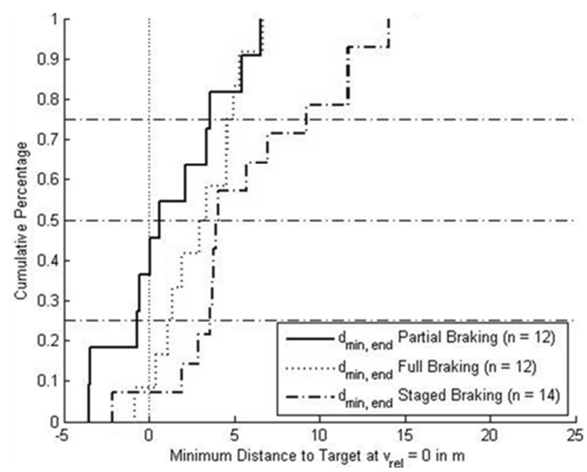

Fig. 9: Minimum distance to target extrapolated for braking strategies without switch off

The differences between partial braking and staged braking are significant.

According to this analysis, partial braking has the highest proportion of potential uncontrollability. In parallel, partial braking shows the lowest mean value for the maximum deceleration. However, the conclusion that partial braking is most critical is not necessarily valid. As described earlier, all drivers react within the first second after the beginning of the situation. If a positive relative deceleration is reached within this reaction, v_{rel} decreases approaching the target. Due to limitations of the test layout, in many cases the trial will be canceled without reaching the Point-of-No-Return. In these trials, the driver still has time left at the end of the trial to increase brake pressure to maximum and avoid collision. This remaining time is called Time-To-Full-Deceleration (t_{tfd}). For the trials considered to be potentially uncontrollable, the minimum distance to the Point-of-No-Return ($d_{PoNR,\,test}$) and the acceleration at the end of each trial ($D_{end,\,test}$) in comparison to the Time-to-Full-Deceleration and the minimum extrapolated distance ($d_{min,\,end}$) ranked by $d_{PoNR,\,test}$ are included in Table 10.

Table 10.
Analysis of Potentially Uncontrollable Trials

	$d_{PoNR,\,test}$ in m	$D_{end,\,test}$ in m/s^2	t_{tfd} in s	$d_{min,end}$ in m
Partial	1.09	8.4	0.13	- 2.49
	4.16	8.1	0.77	- 1.00
	5.27	7.0	0.84	- 3.43
	7.58	8.6	0.98	- 0.52
	9.21	7.3	1.65	- 0.70
Full	6.44	8.4	0.76	- 0.86
Staged	1.34	7.0	0.14	- 2.12

In most cases, the time to increase brake pressure is well above the reaction times previously analyzed. It is assumed that the drivers can react to the evolvement easily and still control the situation. In two cases the t_{tfd} is very short. A concrete controllability assessment is not possible in these cases. Strictly following a conservative approach these cases must be considered to be uncontrollable as no evidence for controllability can be found. Following this argumentation the resulting uncontrollability proportions of the trials ($p_{U,\,Test}$) and the relating number of uncontrollable trials ($n_{U,\,Test}$) are summarized in Table 11.

Table 11.
Uncontrollability Proportions

	n	With Switch Off		Without Switch Off	
		$p_{U,\,Test}$	$n_{U,\,Test}$	$p_{U,\,Test}$	$n_{U,\,Test}$
Partial	12	0.00	0	0.08	1
Full	12	0.00	0	0.00	0
Staged	14	0.00	0	0.07	1

The relevance factor is calculated according to these results, assuming equal controllability for parameter time gap $q = 2$ and $q = 3$ and doubled uncontrollability from $q = 2$ to $q = 1$ with a minimum uncontrollability of 5 %. The results based on simulation (see "Simulation for Initial Controllability Estimation") and tests are included in Table 12.

Table 12.
Relevance Estimation

		Parameter Class: Time Gap ($K = 3$)		
		Categories: 1st Detailing Level		
q		1	2	3
$\rho_{3,q}$		0.25	0.5	0.25
Partial SO/ Staged SO	$g_{3,q}$	0.05	0.00	0.00
	g_3	0.0125		
Partial	$g_{3,q}$	0.05	0.08	0.08
	g_3	0.10		
Full/ Full SO	$g_{3,q}$	0.70	0.00	0.00
	g_3	0.175		
Staged	$g_{3,q}$	0.10	0.07	0.07
	g_3	0.0775		

Results of Subjective Evaluation

The questionnaire showed that all participants were urged to brake (see Fig. 10).

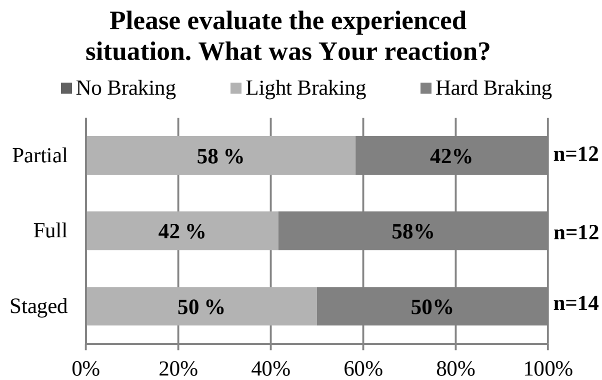

Fig. 10: Subjective evaluation of braking reaction

Even though the overall trend is as expected, it has to be highlighted, that this does not match the results of the distribution of maximum decelerations according to Figure 4. The maximum decelerations could possibly be influenced by the braking assistant, but even then, the function must be triggered by the driver reaction (pedal actuation speed, time to change pedals). The braking assistant should only support the driver if these parameters indicate an intention for an emergency stop. In conclusion the driver seems to be not very reliable at judging his/her own reaction in the aftermath.

In the next step, the risk judgment of the situation is analyzed (see Figure 11).

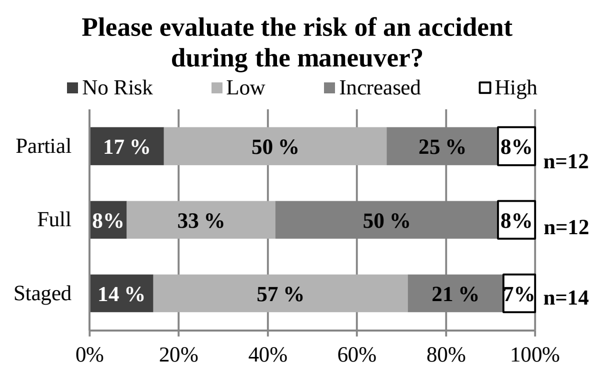

Fig. 11: Subjective evaluation of accident risk

The subjective risk evaluation is relatively similar between partial braking and staged braking. For full braking, the risk is judged to be higher. In Figure 12, the results are compared with the subjective controllability evaluation.

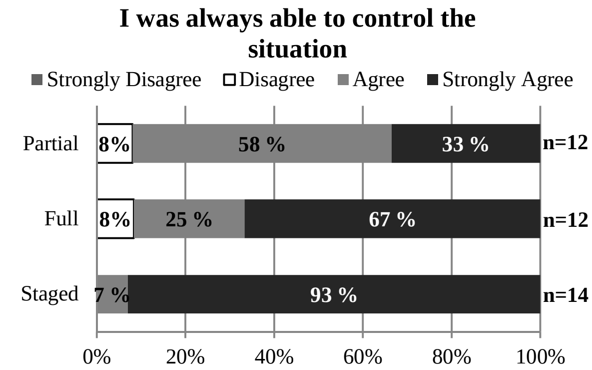

Fig. 12: Subjective Controllability evaluation

It stands out that the proportions of high risk are the same as the “disagree” of controllability for the partial and full collective. A detailed analysis shows that the statements do not directly correspond to each other. Even more remarkably, all trials which are potentially uncontrollable are subjectively evaluated with “Agree” or “Fully Agree”.

Figure 13 shows the direct corresponding proportions between the driver judgment of subjective reaction intensity and subjective controllability.

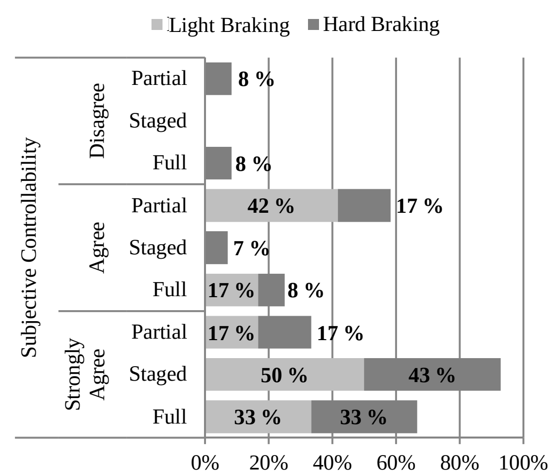

Fig. 13: Subjective Controllability versus reaction overall

For braking strategies with switch off the assessment is correct, with some drivers being more cautious. For braking strategies without switch off, the driver judgment is not correct for some situations, however as they may not approach the Point-of-No-Return during the maneuver, they have less chance to perceive the criticality of the situation.

CONCLUSIONS

A method for identifying and selecting testing situations for controllability has been described and exemplarily applied for a situational parameter. As a next step an assessment method for the controllability assessment was outlined and tests with naïve test subjects were carried out for the identified base case. The testing shows the feasibility of the criterion for subsequent analysis of different situation evolvements, for example considering a switch off of the leading vehicle deceleration.

For strategies with switch off after 1.5 seconds, all trials can be assessed as controllable. Without switch off, the assessment with a simple extrapolating method shows an uncontrollability proportion of one of fourteen trials (7.1 %) for staged braking, one of twelve trials (8.3 %) for full braking, and five of twelve trials (41.7 %) for partial braking. A more detailed analysis reveals that in most of these uncontrollability cases more than 0.75 seconds are available to increase brake pressure and avoid the collision. Considering the remaining time only one trial (8.3 %) for partial braking and one trial for staged braking (7.1 %) are considered to be uncontrollable as the opposite cannot be argued to be valid.

The simulation of lower time gaps indicates that more critical situations are worth testing in real life. However no applicable way to motivate naïve drivers to follow that close was found in the past.

In general, the number of trials per braking strategy used in the present study is relatively low. To further validate the results, the collectives should be enlarged to improve the validity of the assessment. In addition, testing with distracted drivers should be carried out to broaden the knowledge on inattentive drivers.

The test method with EVITA used in here proved suitable for the intended goal. For critical situations where the driver reacts late, it is able to come close to the Point-of-No-Return and trigger a suitable driver reaction. In cases where the driver reacts early but not intensely enough, the method is limited, however these situations are not expected to be most critical.

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